

Faro Mine, Yukon Territory, Canada: a case study for optimising zinc load capture by clean water diversion and focused contact water capture

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Abstract

The Faro Mine, located in the central Yukon, produced lead, zinc, silver, and gold from the late 1960s until 1998, when the mine was abandoned. Seepage from sulfidic waste stored in the Faro waste rock dumps (WRDs) has variably impacted groundwater and surface water reporting to the North Fork of Rose Creek (NFRC), a fish-bearing surface water body, which passes along the toe of the Faro WRDs. Zinc is the primary parameter of concern, reaching several orders of magnitude higher than applicable water quality guidelines, and previous yearly maximum concentrations.

Interception of contact water before it reaches the NFRC has been challenging due to the complex seepage patterns within the WRDs and proximity of the creek. Despite existing collection systems intercepting high concentration seepage pathways, zinc remained elevated in the creek. The NFRC Realignment Project commenced in 2015 to 'keep clean water clean' by diverting the NFRC into the non-contact water diversion channel (NCWDC) and allowing focused collection of WRD seepage in the remnant NFRC channel. The first phase of the contact water collection and conveyance system (CW System) was focused on the interception of shallow groundwater and surface flow in the remnant NFRC. The NCWDC was commissioned on 24 October 2020, and the initial CW System was commissioned on 15 April 2021.

Isolating the clean water through construction of the NCWDC substantially reduced the surface water available for dilution. Both the uncertainty in capturing contact water prior to it reaching the creek and the inefficiency of capturing contact water once mixing occurred with creek flow were mitigated with this approach. A year after commissioning the NFRC Realignment Project, performance monitoring shows measured zinc concentrations in the NFRC approximately two orders of magnitude lower at the downstream monitoring station than realised by previous efforts.

Keywords: *contact water, mine closure, water management, creek diversion, zinc, remediation, pumping, modelling, hydrogeology, hydrology, civil engineering, geochemistry, cold regions*

1 Introduction

The Faro Mine, located in the south-central Yukon Territory, is approximately 200 kilometres (km) north-northeast of Whitehorse in northern Canada. The mine operated from 1969 through 1998 when the last mine owners abandoned the site. In the 1970s, it was the largest producer of lead and zinc in Canada and made up approximately 15% of the world's output of these metals. The Government of Canada, represented by Crown-Indigenous Relations and Northern Affairs Canada (CIRNAC), is the proponent of final remediation of this mine.

The Faro Mine facilities include the ore processing area, waste rock dumps (WRDs), Rose Creek tailings area (RCTA), and the Faro Pit. The WRDs contain over 260 Mt of waste rock and the RCTA contains over 70 Mt of

tailings. The majority of the waste rock and tailings are acid generating and have released acid rock drainage containing dissolved metals into groundwater and surface water features that flow through the site. Seepage from the WRDs has variably impacted groundwater and surface water reporting to the North Fork of Rose Creek (NFRC), a fish-bearing surface water body, which flows along the toe of the WRDs. Figure 1 illustrates the features and locations described within this introduction.

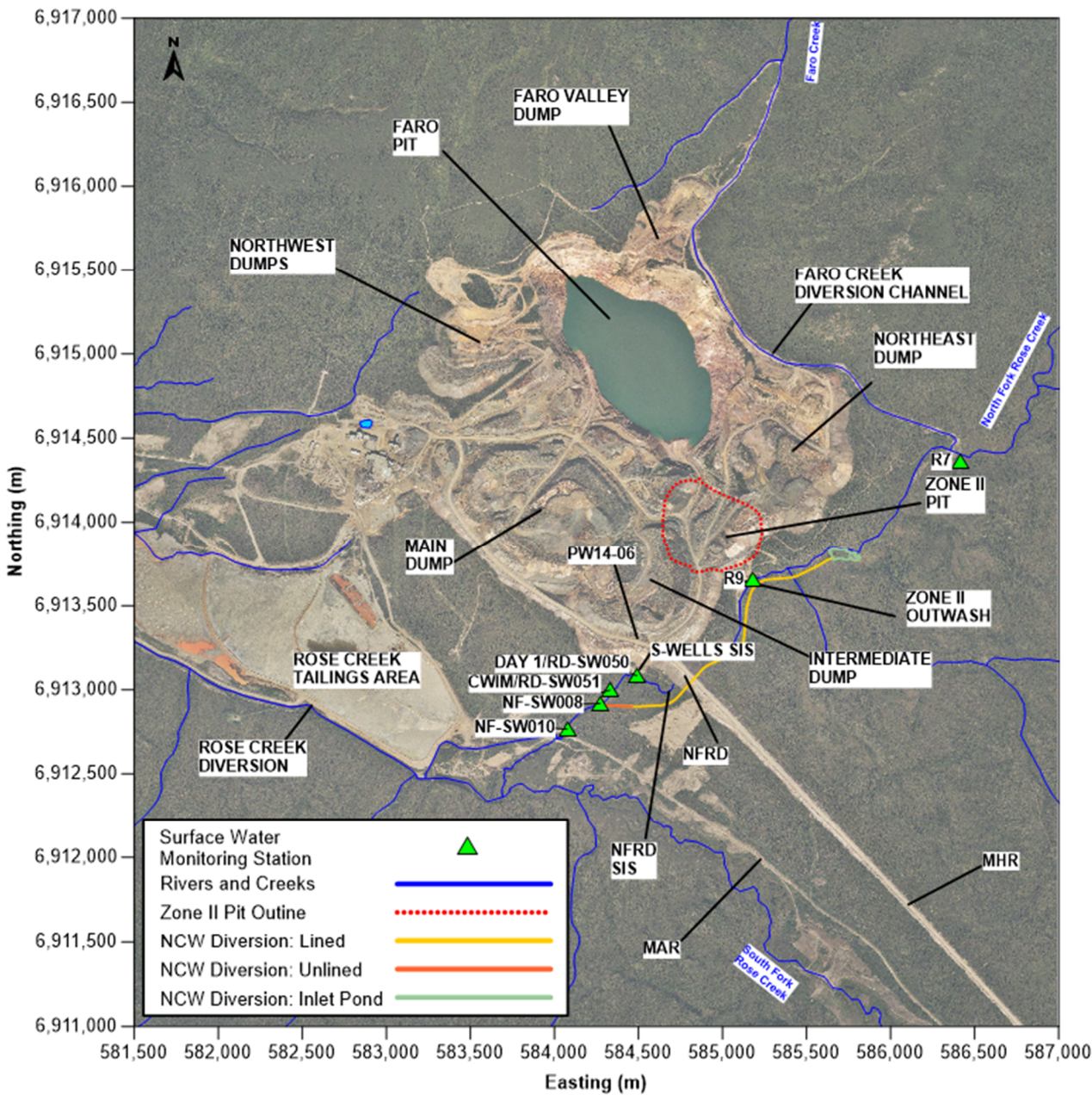


Figure 1 Faro Mine layout and surface water quality monitoring stations

In 2014, the concentration of zinc in the NFRC reached approximately 1 mg/L at the downstream monitoring station (NF-SW010), several orders of magnitude higher than typical water quality guidelines for the protection of freshwater aquatic life (i.e. 0.037 mg/L [short-term exposure]; CCME 2012) and higher than previously observed yearly maximum concentrations. In October 2014, Environment Canada issued a directive to control the contamination and immediately take measures to stop the deposit of a deleterious substance into Rose Creek, located downstream of the mine area. In response, CIRNAC initiated the NFRC Realignment Project as an Urgent Work.

1.1 Site description

The Faro Mine is located within the Central Yukon Basin climate zone and the climate is characterised as sub-arctic continental (Smith et al. 2004). Based on site data collected from 1978 to 2016, mean annual air temperature is approximately -2°C , with July and January mean monthly temperatures of $+12^{\circ}\text{C}$ and -15°C , respectively. Faro typically sees above-freezing mean daily ambient temperatures between the months of May and September and sub-zero mean daily ambient temperatures between the months of November and March. Estimated annual precipitation totals from 1978 to 2016 ranged from 238 mm to 662 mm, averaging 443 mm. Average monthly precipitation is highest from June through October and lowest from February through April.

The NFRC drains south from the Anvil Range and conveys water from the upper NFRC watershed and the Faro Creek Diversion Channel (FCDC) past the WRDs, through a rock drain (North Fork Rock Drain; NFRD) in the Mine Haul Road (MHR), and the Mine Access Road (MAR) crossing (consisting of two culverts), to the confluence with the South Fork of Rose Creek and the Rose Creek Diversion, and eventually back into the undisturbed Rose Creek (Figure 1). The NFRC itself is typically 5 to 10 m wide.

The NFRC is located along the eastern toe of the Main and Intermediate WRDs (Figure 1). North of the MHR, the NFRC floodplain is approximately 100 m to 200 m wide and is bound to the east by hillslopes that slope to the NFRC valley at approximately 4H:1V to 3H:1V and to the west by the WRDs. South of the MHR, the NFRC valley becomes narrower (down to approximately 20 m wide at the floodplain) and is bound by slopes that rise approximately 20 m above the floodplain and range from approximately 4H:1V to the west and 2H:1V to the east. Bedrock outcrops are also visible in the steep slopes east of the creek and adjacent to the creek just north of the MAR crossing. Most of the area along the NFRC is undisturbed and vegetated and frequently covered by small brush and deciduous trees.

The surficial geology of the area is largely a product of glacial activity during the Pleistocene, combined with more recent Holocene modification by fluvial erosion and deposition, as well as colluvial and cryogenic processes. All the surficial materials and glacial landforms that currently exist in the area were deposited in the most recent, late Wisconsin McConnell, glaciation. All but the highest peaks in the area were ice covered during the last glaciation (Bond 2001).

Deglaciation in this region consisted mainly of melting large stagnant ice blocks, a complex system of glaciofluvial deposition, and glacial lake resultant formation and drainage disruptions. Glacial deposits are typically of till, glaciofluvial, and glaciolacustrine origin. During the Holocene, a number of geomorphic adjustments occurred as the landscape transitioned from a glacial to a non-glacial regime, including erosion and colluviation.

A surficial geology map of the Faro area was prepared by Bond (1999), based on field mapping and regional sampling. The map shows that the terrain along the current NFRC floodplain is predominantly alluvial/fluvial deposits, with colluvium and glaciofluvial deposits beneath slopes above the floodplain, and tills at higher elevations. Much of the Faro Mine Complex area is blanketed by McConnell till that is typically less than 20 m thick. In many cases, the till is interbedded with glaciofluvial and glaciolacustrine sediments as a result of complex deglaciation processes and active ice retreat.

The Faro Mine lies in the sporadic and discontinuous permafrost zone, meaning that 10 to 50% of the ground is underlain by permafrost. Geotechnical investigations in the NFRC valley indicate that permafrost, where present, is generally warmer than -1°C and of thickness ranging from approximately 2 m to greater than 20 m, with the thickness decreasing with increasing distance away from the MHR. Ground ice content varies, both spatially and with depth, and depending on the soil texture. Both ice-poor permafrost (visible ice content less than approximately 10% by volume, or the material is in a damp to moist state when thawed) and ice-rich permafrost (visible ice contents exceed approximately 10% by volume or the material is in a saturated or wet state when thawed) are present.

The segment of the NFRC that flows along the eastern toe of the WRDs receives mine-impacted seepage from the adjacent dumps. As discussed, much of the waste rock stored in the Faro WRDs is classified

(according to MEND 2009) as potentially acid generating (PAG). The Northeast WRD (NE WRD) is largely composed of waste rock classified as non-PAG, with smaller, localised hotspots of sulfidic waste material anticipated to occur. The Zone II WRD is largely composed of non-PAG waste rock, with no identified localised pockets of sulfidic waste. The Intermediate and Main WRDs, which store the bulk of the waste rock, were constructed with sulfide waste cells in the upper lifts with the intention of isolating the more reactive sulfide waste in layers of non-PAG material and promote alkaline pH seepage. The use of segregation/encapsulation appears to have been limited to later in the mine life (Pigage 1990).

Zinc is the primary parameter of concern for the NFRC Realignment Project. Increasing dissolved zinc concentrations have been observed along the NFRC from the surface water monitoring station located just downstream of the non-contact water diversion channel (NCWDC) inlet (R9) to the project receiving water station, NF-SW010 (Figure 1).

1.2 Background

The design objective of the NFRC Realignment Project was to improve water quality at the downstream receiving water station to be protective of aquatic life. The NF-SW010 monitoring station was selected for the NFRC Realignment Project due to its location downstream of the proposed remedial works and upstream of the influence of other mine facilities (e.g. the RCTA).

Actions to address the zinc impacts to the NFRC prior to and following the 2014 Environment Canada directive included the following: focused withdrawal of seepage with elevated zinc concentrations that had been encountered during site investigations, using pumping wells and a sump (the S-Wells seepage interception system [SIS]), and an attempt to intercept a more disperse seepage flow path discharging to the NFRC underneath the MHR (the NFRD SIS; Figure 1).

Site investigation in 2005 (prior to Urgent Works) had identified a narrow zinc seepage plume at the toe of the WRDs downstream of the MHR. Zinc concentrations within this plume reached 400 mg/L and higher. These investigations resulted in the implementation of the (previously mentioned) S-Wells SIS pumping system in 2008 that included an interception trench and pumping wells targeting that identified plume. Later, in 2014, a pumping well targeting another high concentration zone (PW14-6) was added to the overall capture effort in this area (upstream of the S-Wells SIS). Both of these systems convey the captured water via pipeline to the Faro Pit for storage and later treatment. While both of these systems have been able to successfully capture groundwater with high zinc concentration, efficient pumping rates are limited by the relatively small, targeted seepage plume, which limits the overall load removal and mitigation of zinc load reaching the NFRC.

In response to the increase in zinc concentration in 2014 that gave rise to the Environment Canada directive, the former site manager, Yukon Government, implemented initial remedial responses during the fall and winter of 2014/2015 by constructing the (previously mentioned) NFRD SIS (Figure 1). This system was designed and installed utilising existing site data as a 'best efforts' attempt to mitigate the rise in zinc concentrations within the NFRC. A localised seepage collection system with all-weather pumps and piping was constructed just downstream of the NFRD to collect identified contaminated seepage discharging on the western side of the NFRD and convey the seepage to the Faro Pit for temporary storage and later treatment. This system was only partially effective in capturing the contaminated seepage, as the water reaching the NFRD SIS was diluted by clean surface water flows within the NFRC. In addition, this SIS had a limited-extraction capacity, which meant that elevated zinc still existed in the lower section of the NFRC at select times of the year.

While the S-Wells SIS was found to succeed in capturing significant zinc load prior to it reaching the NFRC, additional measures were required to mitigate zinc levels measured at NF-SW010 to below guidelines. Zinc load removal from the NFRD SIS did not significantly reduce concentrations at NF-SW010; the system ceased operation in April 2017 and was later decommissioned. Figure 2 presents dissolved zinc concentrations from January 2007 to January 2022, showing seasonal fluctuations, and a general rising trend with time, including a notable increase in seasonal peaks starting in 2014. The limited impact on zinc concentration trends at

NF-SW010 in response to both the S-Wells SIS and the NFRD SIS is shown in this figure. The break in this trend in 2020 and beyond is discussed in later sections.

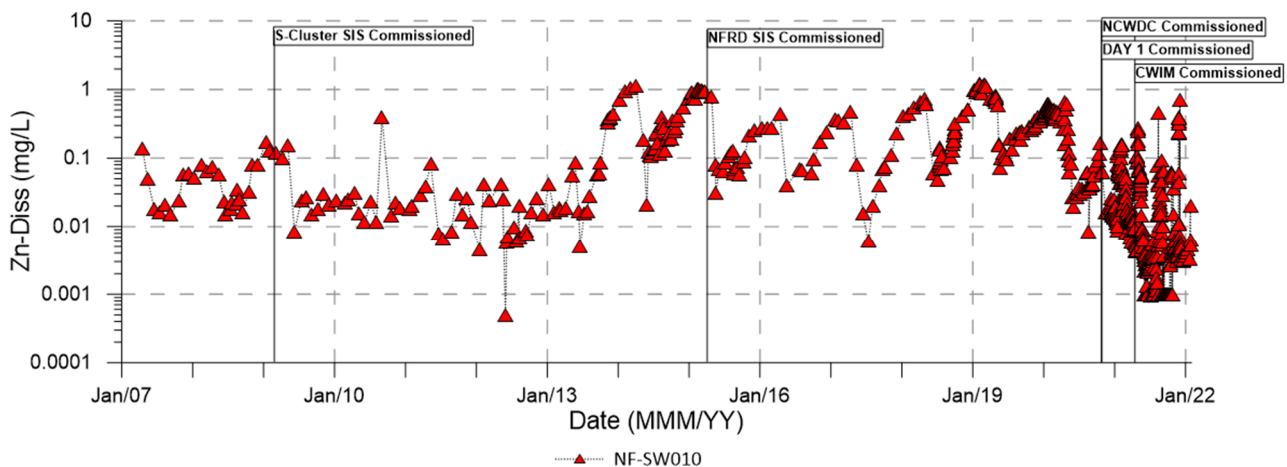


Figure 2 Dissolved zinc concentrations at NF-SW010 from January 2007 to January 2022

The NFRC Realignment Project was developed to divert the diluting (clean) water flow away from the receiving creek bed so that zinc loads reaching that creek could be identified and removed effectively. The NFRC Realignment Project was divided into two separate but related design components: a NCWDC, and a contact water collection and conveyance system (CW System).

The NCWDC separates clean water from the NFRC watershed, upstream of the WRDs, from current and future mine-impacted water migrating from the WRDs towards the NFRC. This separation is achieved by diverting the NFRC flows beginning near the southwest toe of the Northeast WRD (i.e. an area considered to be negligibly impacted by WRD seepage) into a 1.9 km long engineered channel, which rejoins the NFRC channel downstream of the WRDs. The NCWDC is a partially lined channel constructed on the opposite side of the NFRC valley from the WRDs and at a higher elevation than the existing NFRC channel. Construction in preparation for the NCWDC began in February 2019 and the channel was commissioned on 24 October 2020.

Work associated with the CW System included the design and implementation of an initial system, referred to as the contact water interim measure (CWIM). The CWIM is designed to intercept, capture and convey WRD-impacted seepage migrating as surface water and shallow baseflow along the remnant reach of the NFRC (or old NFRC) following diversion of the majority of surface flows to the NCWDC. The CWIM is composed of a 3 m deep trench and sump excavated below the existing NFRC stream bed and backfilled with drain rock. The CWIM was winterised to allow for year-long operation and conveys the collected WRD-impacted water to the Faro Pit for temporary storage and ultimately water treatment prior to release to the environment. The design of the CWIM assumed storm events or flow conditions greater than average would bypass capture. Construction of the CWIM commenced in November 2020, with temporary measures instituted in October 2020 and the CWIM system being commissioned on 15 April 2021.

2 Design methodology

2.1 Conceptual site model

Six main hydrostratigraphic units (HSUs) were identified in the NFRC valley (from surface to depth): colluvium, alluvium (i.e. including both active [fluvial] coarser grained sediments and inactive [alluvial] siltier materials), glacial till, glaciofluvial sediments, weathered bedrock, and bedrock. The colluvium is observed as thin veneers (i.e. up to a few metres thick) on the upper slopes near the toe of the WRDs and frequently overlies shallow bedrock. Alluvium is present at variable thicknesses (up to 10 m) along the lower slopes and floodplain of the NFRC valley, with siltier or finer grained (alluvial) material giving way to gravelly sands

(fluvial) towards the existing creek bed. A sequence of glaciofluvial sediments underlies the alluvium that, upstream of the MHR, contains pockets and/or discontinuous, thin lenses of glacial till.

A weathered bedrock layer of variable thickness (i.e. a few metres to > 10 m) underlies the unconsolidated sediments deposited in the NFRC valley. The depth to bedrock near the channel bottom decreases downstream of the CWIM, with bedrock within a few metres of surface to exposures at surface. The shallower depth to bedrock at these downstream reaches is also concomitant with a 'pinching out' or thinning of the overlying alluvium and glaciofluvial HSUs; the subsurface in these areas is interpreted to be mostly composed of glacial till overlying bedrock.

Mobilisation of contaminants from the WRDs begins with infiltrating rainfall and snowmelt during the open water season from May to October, with negligible surface runoff except in trafficked areas of compacted material where the rate of infiltration is restricted. Wide ranges in WRD particle sizes lead to heterogeneous distributions of hydraulic conductivity and soil moisture content, resulting in highly variable rates of infiltration. The complex combination of WRD reaction and infiltration rates leads to a contaminant source function with highly variable kinetic release rates. This variability manifests as a spectrum of zinc input loads to the groundwater system over both space and time.

A portion of the mass loading from the WRDs discharges to surface water along the length of the NFRC downstream of the confluence with the FCDC via the shallow, higher hydraulic conductivity HSUs. Some WRD-impacted water is interpreted to infiltrate to the deeper groundwater in the glaciofluvial and weathered bedrock HSUs; a portion of this deep groundwater was assumed to upwell and discharge between the CWIM and NF-SW010, and a portion was assumed to discharge downstream of NF-SW010.

Figure 3 presents a graphical representation of the conceptual site model described herein, representing sections adjacent to the WRD (generally upstream of the MHR).

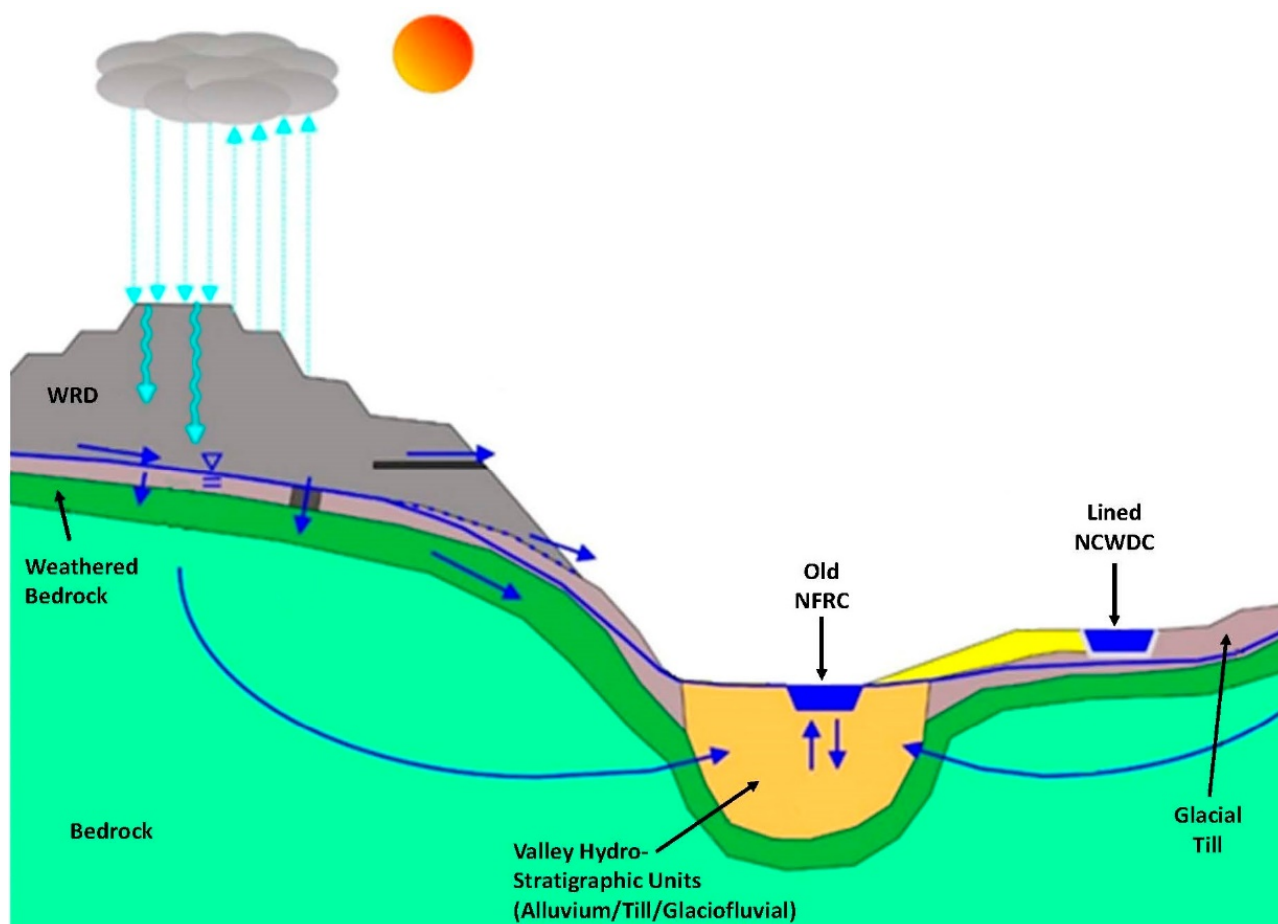


Figure 3 NFRC conceptual site model

2.2 Design studies

Contact water collection and conveyance system design effort up to 2018 was focused on the broader phased system and this system is referred to as the CW System. Later design efforts that were focused on implementation of the initial phase of the CW System refer to that specific initial system as the CWIM.

2.2.1 *Site investigations and monitoring*

A number of site investigations were undertaken from spring 2015 to October 2018, in support of options analyses, design and construction planning of the NCWDC and CW System. These investigations included over 170 boreholes, almost 300 test pits, surface and downhole geophysics, and a permafrost test cut. In addition, site investigation information collected before 2015 was also compiled where relevant to the NFRC Realignment Project.

In addition to the investigations listed above, surface water, groundwater and geotechnical monitoring programs were undertaken to collect data in support of the NFRC Realignment Project. These programs included general ongoing site-monitoring programs and a contact water monitoring program (CWMP) that was developed in 2018 to document groundwater and surface water quantity and quality within the NFRC valley before and after diversion, and to inform design of the CW System. This CWMP program incorporated 43 groundwater monitoring locations, eight surface water monitoring stations, and five existing seep locations when flowing.

2.2.2 *Hydrology modelling*

Surface runoff modelling approaches were completed for both monthly average precipitation and storm events.

Pre-diversion average monthly stream flows within the NFRC ranged from 0.23 m³/s to 3.40 m³/s (average annual streamflow of 1.24 m³/s). These flows are based on monitoring station R7 data, located upstream of the NCWDC inlet (Figure 1), scaled to a location at the MHR. The NCWDC was designed to convey flows for the 1:200-year flood event of 78 m³/s, with 0.3 m of freeboard. However, the relevant comparison to the post-diversion NFRC flows is the average annual flow rate.

Surface runoff estimations within the abandoned NFRC involved delineating the contributing area to intercept precipitation that may report as runoff (i.e. basin delineation) and report to the area of the CWIM. The catchment areas reporting to the CWIM location were estimated to be 12,400 hectares (ha) (124 km²) before diversion and 69 ha (0.69 km²) after diversion. The catchment after diversion consisted of 41 ha of uncovered waste rock and 28 ha of 'undisturbed' area.

Post-diversion hydrologic modelling of the waste rock area indicated negligible surface runoff with annual net percolation ranging from 130 mm to 160 mm. Streamflow data were used to define the total runoff and average discharge for the 28 ha of undisturbed area for average, wet and dry years. An above-average precipitation (wet) year was defined as one standard deviation higher than the mean monthly discharge during the 1997–2015 period, while a below-average precipitation (dry) year was defined as one standard deviation less. The average surface water discharge reporting to the CWIM location from the 69 ha area is approximately 5.1 L/s for an average year, 6.4 L/s for a wet year and 3.7 L/s for a dry year.

The average predicted flow rate at the CWIM location following diversion (5.1 L/s or 0.005 m³/s) is therefore 0.4% of the average annual pre-diversion flow (1.24 m³/s) – a reduction factor of 250.

2.2.3 *Hydrogeology modelling*

A numerical groundwater flow model for the NFRC and RCTA was developed using the MODFLOW-USG (Panday et al. 2013) flow code and the Groundwater Vistas (Version 7.24 Build 255; Rumbaugh & Rumbaugh 2017) graphical user interface. The model was calibrated using site-wide groundwater monitoring data, then run to simulate the inclusion of the NCWDC and CWIM. The model was used to predict average annual

groundwater conditions following implementation of the CWIM using steady-state simulations, and to predict average annual flows captured by the CWIM. Sensitivity analyses were run for predictive steady-state models representing implementation of the CWIM, to assess the groundwater and surface water contributions to flow intercepted by the CWIM and assess the CW and NCW flow contributions for various segments of the old (or diverted) NFRC channel.

Steady-state simulations were used to predict average annual flows to be captured by the CWIM. Simulated flows range from 3.8 to 22.7 L/s. This range incorporates sensitivity analyses to account for uncertainty in hydraulic properties and model recharge. Most (i.e. > 95%) of this flow is predicted to be surface water flow within the remnant NFRC channel. Transient simulations were run using the base case scenario to examine seasonal variations in flow captured by the CWIM for average, above-average precipitation (wet), and below-average precipitation (dry) years. Predicted flows captured by the trench are greatest in May (snowmelt period), ranging from 7.3 L/s (dry year) to 12.8 L/s (wet year), and decrease to minimum values that approach 4 L/s (winter period) for the transient seasonal simulations using the base case hydraulic properties. These ranges exclude uncertainty due to variation in hydraulic properties.

The predicted flow within the shallow alluvium HSU that bypasses the CW interception trench is negligible for average annual conditions; however, in practice, some portion of groundwater flow within the alluvium may bypass the CW interception trench when pumping at an average rate of 20 L/s. The predicted bypass flow within the glaciofluvial and weathered bedrock HSUs for average annual conditions ranged from 0.1 to 2.3 L/s, with < 0.1 to 1.2 L/s of this flow predicted to discharge downstream of NF-SW010.

2.2.4 Water quality modelling

An Excel-based load balance model was developed that assumed mass conservation and complete mixing, and did not include geochemical reactions that might attenuate mass reaching the creek. To support the design of the CWIM, eight contributing areas were defined on the right and left banks of the NFRC channel and source terms were developed for the water quality model to reflect surface and groundwater quality contributions from each area. The source terms were combined with groundwater, surface water and surface runoff inflows and the residual impacts evaluated under both steady-state and transient scenarios.

The model was used to predict the quality of water at the NF-SW010 surface water monitoring station after diversion of the NFRC into the NCWDC and operation of the CWIM. Zinc concentrations in the water intercepted by the CWIM trench were predicted to range from 12 to 30 mg/L. The simulated zinc concentrations were used to estimate the zinc mass that would be captured and therefore no longer report to NF-SW010. Zinc concentrations in the NCWDC were predicted to range from 0.001 to 0.006 mg/L.

2.3 Clean water diversion: NCWDC design

Physical separation of the non-contact and contact water was to be achieved by an engineered channel mostly constructed within the NFRC valley. The NCWDC was to direct flow of non-contact water through this engineered channel with an inlet located upstream of the interpreted impacted seepage points and return it back into the NFRC at a lower elevation, with an outlet upstream of the MAR crossing.

The major elements of the NCWDC include the following:

- A low-head dam at the inlet of the diversion channel, which forms a pond (fish overwintering habitat) and diverts flow from the upstream NFRC catchment into the channel.
- A diversion channel (1.9 km long), hydraulically isolated from natural surface water flow by elevation (above the NFRC valley bottom), with a geomembrane liner for the majority of its length.
- A pilot channel to mitigate glaciation or ice blockage during low-flow periods of winter.
- Excavation of over 600,000 m³ of waste rock from the MHR, through which the NCWDC crossed.

- The NCWDC design was completed in 2018 and construction of the channel was undertaken in 2019/2020.

2.4 Contact water capture: CW System design

A detailed options assessment undertaken in 2017 and 2018 identified three options to be considered for CW collection. Two options comprised a collection trench excavated below the watertable perpendicular to the prevailing groundwater flow direction (i.e. cross-valley) and offset towards the WRD-side of the NFRC. Contact water intercepted by the trench would be directed towards a sump for localised extraction and conveyance towards the Faro Pit for further management. The third option comprised pumping wells screened to 10 m depth and a mini-trench limited to the creek channel. For all options, the trench or mini-trench would be designed to intersect the NFRC stream bed to collect baseflow in the channel; flood events would be allowed to pass.

The CW System options above were designed to a conceptual level based on available site information and data. Site investigation was intended to finalise the option selection and support detailed design of the selected option. Further, it was intended that the CW System would be installed in a phased manner, so that subsequent phases would be informed by the construction and performance experience of the prior phase(s).

2.4.1 Contact water interim measure design

Design of an interim measure based upon the CW System options analysis was initiated in April 2020, to allow a system to be constructed in time for the commissioning of the NCWDC, which was anticipated to be in the fall of 2020. Given the limited time frame for design, procurement and construction of the CWIM, a limited site investigation was undertaken to refine design inputs and inform detailed design. The interim nature of this CWIM was an application of the phased approach considered during options analysis. This CWIM design focused on capturing groundwater baseflow as the initial design or phase of a multi-phased system, with the ability to be upgraded in the future.

The major elements of the CWIM include the following:

- A ~25 m collection trench extending from a 2.1 m diameter sump across the NFRC creek bed.
- A compacted gravel pad to support a pump house.
- A winterised pump house installed over the sump with two 20 hp pumps and controls, with fixed electrical power supply:
 - Together with the pipeline configuration, giving a pumping capacity of up to ~20 L/s.
- A 200 mm diameter insulated and heat traced pipeline, installed from the pump house to Faro Pit.

2.4.2 Future expansion

With the limited site data available to support design of the CWIM, expansion was planned to respond to realised conditions following diversion of the NFRC, observed performance of the initial CWIM, and the bypass occurring in pathways not intercepted by the CWIM (i.e. glaciofluvial and weathered bedrock HSUs). In addition, there is potential to include impoundment capability to capture runoff events, as such events were not included in the design of the CWIM.

3 Implementation

Preparatory work for construction of the NCWDC occurred in August 2018 and included installation of fish barriers and salvage of fish from the construction zone. Construction of temporary diversion channels to support construction of the NCWDC (whose footprint was in places on top of the existing NFRC channel) occurred from February to June 2019. The NCWDC itself was constructed from July 2019 to November 2020 and commissioned in October 2020.

As the CWIM was not anticipated to be operational at the time of NCWDC commissioning, a temporary pumping system, referred to as the Day 1 Sump, was constructed to capture and convey surface water remaining in the old NFRC to the Faro Pit. The Day 1 Sump was installed adjacent to the creek, approximately 200 m, upstream of the CWIM trench location, with the existing S-Wells pipelines used to convey pumped water to the Faro Pit. This system was commissioned at the time of NCWDC commissioning and continues to operate, providing backup during CWIM initial operations and additional pumping capacity during high-flow periods. In the longer term, the Day 1 Sump is intended to be utilised as a supplementary system to the CWIM. The capacity of the Day 1 Sump is limited by the available conveyance pipeline capacity, which is approximately 9 L/s via the S-Wells pipeline.

The construction proceeded as follows:

- The CWIM collection trench and pad were constructed in the first half of November 2020.
- Conveyance pipeline construction was largely completed in November 2020, with testing in early December. The installation of pipeline heat trace cables was delayed, resulting in final commissioning of the pipeline in April 2021.
- Construction of the electrical power supply system was initiated in late November and completed in early December 2020.
- Pump house fabrication was completed offsite, at the vendor's facility, in October 2020. The Pump house was shipped to site and installed at the sump location in November 2020. Initial system testing was completed in December 2020, with final testing and commissioning occurring in April 2021, when the pipeline was ready to operate.

The completed CWIM was commissioned in April 2021.

Twenty-one monitoring wells were installed (in seven nests) in October 2020, to be incorporated with three existing monitoring wells and existing surface water monitoring stations to provide the capability to assess the performance of the CWIM. Additional weirs were installed in the old NFRC to enhance surface water quantity monitoring capability.

Following commissioning of the NCWDC, CWIM and Day 1 Sump, the care and maintenance (C&M) contractor for the Faro Mine has operated these systems. Performance data is compiled by C&M, including operational status of the system over time, and monitoring results for surface water and groundwater flow and quality.

4 Results

Monitoring of creek flows along the NCWDC since commissioning has been sporadic due to challenges in measurement of flow during winter conditions; only four measurements were collected between July 2021 and January 2022. Flows measured at the outlet to the NCWDC (NF-SW008) since commissioning have ranged from 226 L/s (April 2022) to 3,170 L/s (August 2021); however, flow likely ranges both lower and higher than this range during winter conditions or spring freshet. Along the old NFRC, flow measurements were not collected regularly. Pumping rates at the Day 1 Sump were approximately 9 L/s beginning in August 2021, while pumping rates at the CWIM varied between 10 and ~20 L/s over the course of 2021. Measured flows downstream of the CWIM (at monitoring station RD-SW020, representing flows bypass of both collection systems) averaged 1.2 L/s.

The CWMP initiated in 2018 to document groundwater conditions in the NFRC valley prior to diversion, and monitor responses to diversion, has shown deteriorating water quality conditions (i.e. rising zinc concentrations) in 2021. Figure 4 presents the lower reach of the NFRC and the various groundwater and surface water monitoring stations (see Figure 1 for upstream monitoring stations). Figure 5 illustrates this trend within CWMP wells, with concentrations at monitoring well FA-MW1027A, located near the Day 1 Sump location and screened within the glaciofluvial HSU. The CWIM performance monitoring program also found increasing zinc concentrations in groundwater in most of the 24 performance monitoring wells; particularly within the glaciofluvial HSU, which is not intercepted by CWIM extraction efforts. Figure 6

illustrates this trend in wells upstream of the CWIM and screened within the glaciofluvial HSU. These increases in concentration are attributed to the removal of diluting water from the NFRC that is now hydraulically isolated for most of the diversion length. A few more rapid increases are noted within this set of wells (i.e. FA-MW1125 and FA-MW1126); however, the drivers for these steeper increases have not yet been determined.

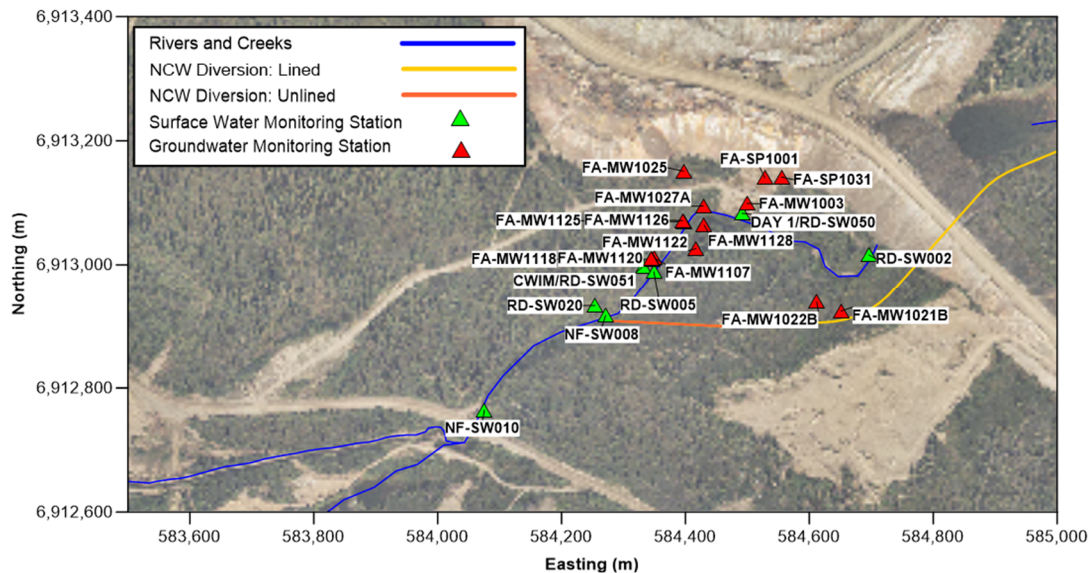


Figure 4 Faro NFRC Realignment Project location map

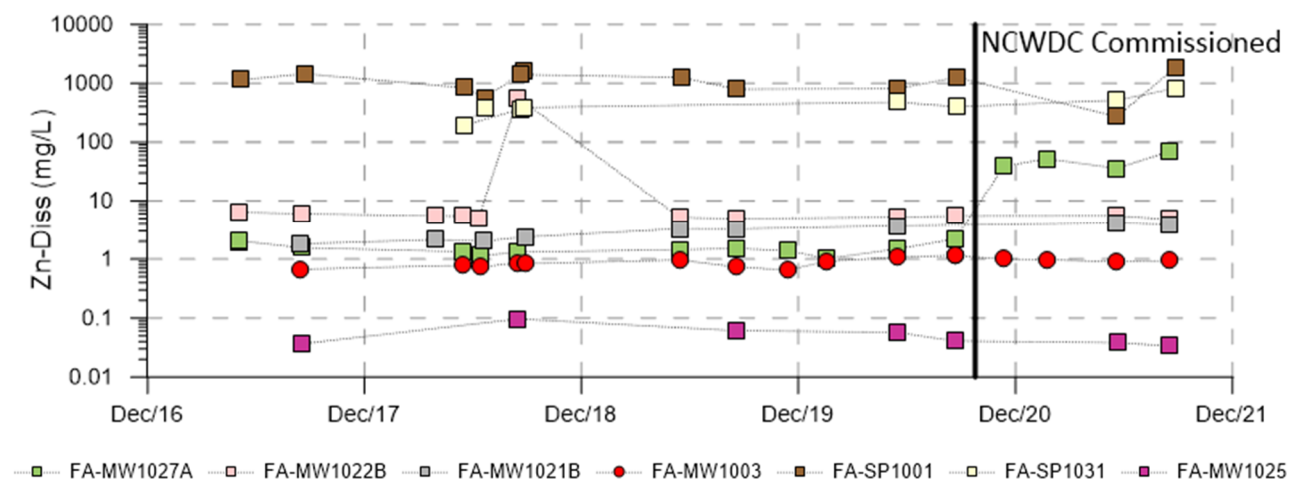


Figure 5 Dissolved zinc time series plot for groundwater monitoring stations near CWIM (CWMP wells)

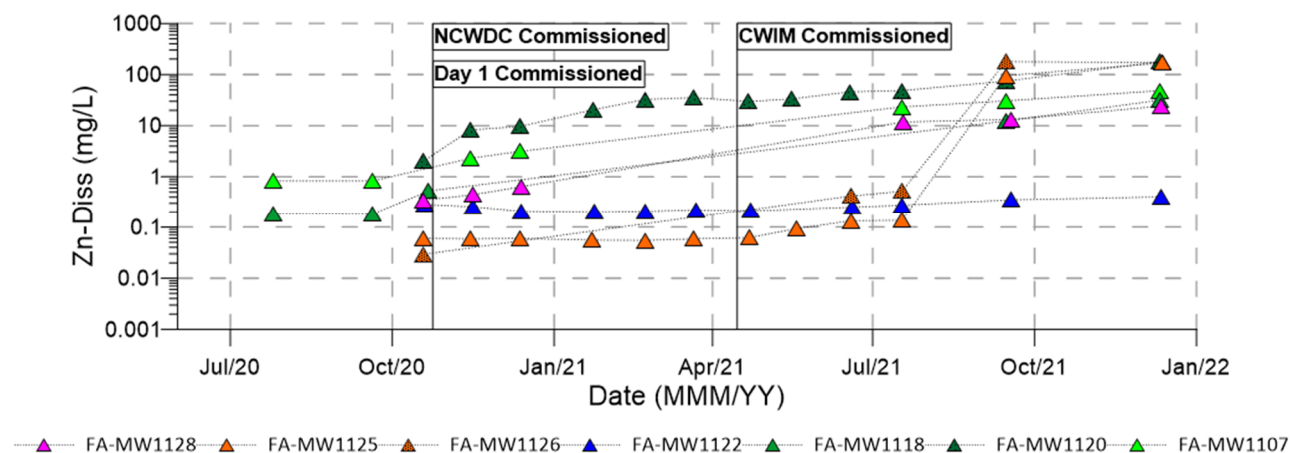


Figure 6 Dissolved zinc time series plot for CWIM performance monitoring groundwater stations near CWIM screened in glaciofluvial unit

In addition to the groundwater quality trends noted above, zinc concentrations in surface water within the abandoned NFRC channel have also been increasing since diversion. Figure 7 illustrates this trend at several monitoring stations along the old NFRC. RD-SW002 is located just upstream of both the Day 1 and CWIM systems; RD-SW005 is located between the Day 1 Sump and CWIM system, RD-SW020 is located downstream of both systems but upstream of the confluence with the NCWDC, and NF-SW010 represents the water quality after confluence between the old NFRC and the NCWDC (Figure 4). NF-SW008 represents the water quality at the outlet of the NCWDC before mixing with the old NFRC flows.

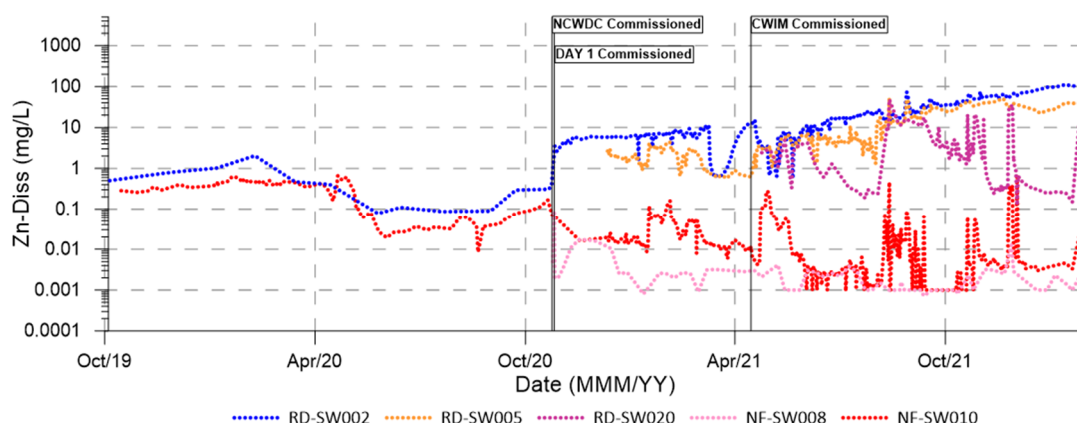


Figure 7 Dissolved zinc time series plot for surface water monitoring stations

The surface water concentrations presented in Figure 7 clearly illustrate both the rising trend in zinc concentrations within the abandoned NFRC channel following diversion (RD-SW002), and the significant reduction in zinc concentrations in the NFRC downstream of the remedial systems (NF-SW010). The impact of the CWIM and Day 1 Sump are further highlighted by the consistently low concentrations when these systems are operating, as well as the immediate rise in concentrations during interruptions in operation of those systems.

Zinc concentrations in pumped water captured by the Day 1 and CWIM pumping systems are presented in Figure 8. Both systems exhibit a rising concentration trend reflective of the trends observed at RD-SW002 and RD-SW005 above. A notable departure in relative concentrations was observed following a winter maintenance shutdown of the CWIM in November 2021. The reason for this departure is not yet clear. It is suspected that the low winter flows are primarily captured by the upstream Day 1 pumping system, leading to more diluting shallow groundwater captured by the downstream CWIM. Or it may be related to icing up of the CWIM trench during the shutdown, as ambient temperatures during this shutdown were colder than -20°C .

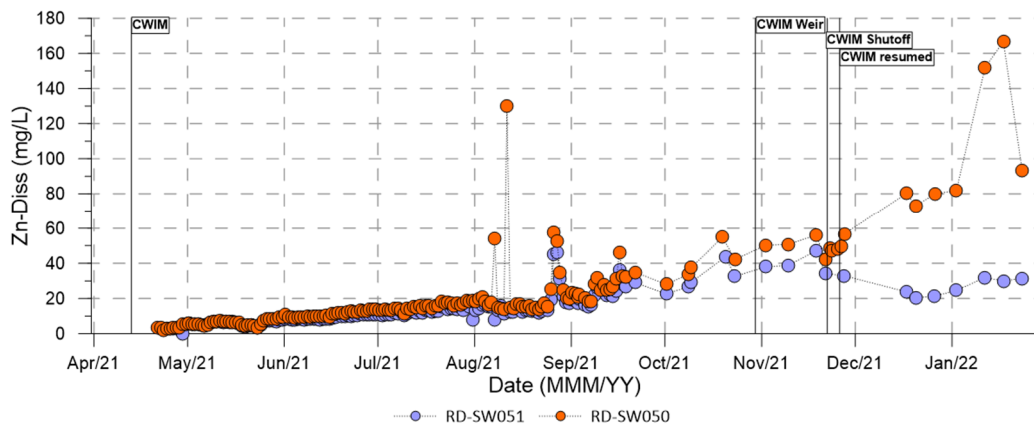


Figure 8 Dissolved zinc time series plot for water pumped from the CWIM (RD-SW051) and Day 1 (RD-SW050) systems

Table 1 summarises the zinc loads captured by both the Day 1 Sump and CWIM system from CWIM commissioning from April 2021 to January 2022. The date ranges reflect time periods when both systems were consistently operational, such that comparison could be made and the total load removed and calculated. Combined zinc load removal at the Day 1 Sump and CWIM has been effective; pre-diversion loads at NF-SW010 were calculated to be 10 to 30 kg/day, and those calculated for 2021 were 0.5 kg/day.

Table 1 Comparative load removal between the Day 1 Sump and CWIM Sump

Heading	15 Apr 21 to 27 Jan 22	24 May 21 to 2 Oct 21	25 Oct 21 to 24 Nov 21	29 Nov 21 to 27 Jan 22
CWIM flow (L/s)	13.9	19	10.5	6.2
CWIM concentration (mg/L)	14.4	14.5	38.7	27
CWIM load removed (kg/d)	20	24	34	13
Day 1 Sump flow (L/s)	8.4	9.9	9.2	9.2
Day 1 Sump concentration (mg/L)	22.5	18.8	49.8	95.2
Day 1 Sump load removed (kg/d)	25	25	39	76
Combined load removed (kg/d)	45	49	73	89

Note: flows and concentrations are calculated averages of measurements taken in the period shown.

5 Conclusion

The surface water quality data collected following diversion of the NFRC (i.e. commissioning of the NCWDC) indicate that the NCWDC is successfully isolating clean surface water from WRD-impacted contact water. Surface water quality in the old NFRC is becoming more reflective of what would be expected from an undiluted contact water plume and observed trends indicate that the concentrations are continuing to increase. The CWIM performance monitoring data also suggest that the focus on collecting surface and shallow groundwater at both the Day 1 and CWIM pumping systems has resulted in improvements to the zinc concentrations at NF-SW010.

Water quality at NF-SW010 over time, as shown in Figures 2 and 7, illustrates the long-term rising trend in zinc concentrations that persisted through previous remedial efforts. Significant reduction and a departure from this trend were realised upon commissioning of the NCWDC, Day 1 Sump and CWIM system. Since the commissioning of these systems, their effectiveness is further highlighted by the significant and immediate response (i.e. rising zinc concentrations) when operation of the pumping systems is interrupted.

To underscore the positive outcome of the NFRC Realignment Project, the Letter of Direction issued by Environment Canada in October 2014 was closed on 7 December 2021.

As has been noted in this paper, the CWIM (and its supplemental system, the Day 1 Sump) is focused on capturing water flowing within the creek and shallow groundwater within the alluvial HSU. The rising concentrations within the glaciofluvial HSU are bypassing these collection systems and may be resulting in some of the residual impacts being seen at the downstream monitoring stations, and possibly some of that loading may be reaching the surface water downstream of monitoring station NF-SW010. Expansion of the contact water systems would be necessary to access these deeper zinc loads – most likely with pumping wells designed to maximise the capture of zinc plumes migrating within the glaciofluvial HSU.

In addition to accessing the deeper groundwater flows, additional bypass is occurring when the surface water flows in the old NFRC exceed the pumping capacity of the Day 1 Sump and CWIM system. This bypass occurs during freshet and significant runoff events. The impact of this bypass on downstream concentrations is mitigated somewhat by a parallel increase in flow of clean water through the NCWDC during those same events. However, other expansion of the CW systems, such as increased pumping capacity or adding impoundments that retain certain runoff events, could be implemented.

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